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Optimal tensiometer placement for high-frequency subsurface drip irrigation management in heterogeneous soils

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ABSTRACT

Efficient control of irrigation systems depends on attaining representative water status data for an irrigated field. The spatial variability of soil hydraulic properties and root growth patterns, hamper the use of single-value representations. This work proposes a two-pronged approach designed for determining optimal sensor location for irrigation water management. It combines experimental results, which offer a method of pre-determining root growth patterns, with modeling analysis in which the effect of tensiometer location on coefficient of variation (CV) of matric head measurements and irrigation system operation was investigated.

In the experimental part, the effect of a geotextile material, wrapped around the drippers along the drip line to create a "Geotextile Drip Interface" (GDI), on root growth patterns in the field was evaluated. The results showed higher root density around the GDI vs. regular buried drippers, with well-defined peak root density in the former vs. no one location with peak root density in the latter. Genetic root architecture had smaller effect on root distribution under the GDI treatment.

The modeling part consisted of HYDRUS 2D/3D simulations of high-frequency subsurface drip irrigation in heterogeneous soils with GDI root distribution as observed in the experiment. The simulations explored different locations for tensiometer placement which will result in low variability of system operation. HYDRUS 2D/3D simulations showed that the optimal location for tensiometer placement is near the subsurface dripper, resulting in low CV of matric head measurements and applied irrigation water, high sensitivity to irrigation, and lower drainage below the root zone.

Overall, the results show that measuring soil water status with tensiometers located close to drippers in GDI volume, improve control of high frequency irrigation systems and allow greater water application efficiency in drip irrigated fields.

1. Introduction

Drip irrigation scheduling uses soil water status to determine timing and amount of irrigation. Many high frequency drip irrigation systems utilize sensor-based monitoring to provide real-time soil water status. Tensiometers, that measure soil water matric head (ψ), are simple and reliable instruments (Cassel and Klute, 1986) used for irrigation scheduling (Or, 2001). Recent advances in drip irrigation technologies enable ultra-high frequency irrigations that match irrigation rates with crop root water uptake, based on triggering criteria. In such systems, there is less dependence on soil water storage capacity but more on soil hydraulic conductivity, because of the high application rates (Dabach et al., 2013; Phene and Howell, 1984). Moreover, temporal variations in root water uptake patterns are avoided, because water supply is almost continuous. Even so, spatial variation in soil hydraulic conductivity and root distribution leads to high coefficients of variation (CV) of ψ, thus complicating irrigation management decisions. To effectively control high-frequency irrigation systems, variability of tensiometer measurements should be avoided and sensors should be placed in locations with representative root zone uptake dynamics.

In a drip-irrigated field, where water is applied from discrete sources, variability in soil water distribution is inherent. This

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non-uniformity, coupled with spatially variable plant root architecture around the drippers, complicates the decision in representative tensiometer placement (Or, 1995). Recommendations for tensiometer placement are empirically or physically based (Coelho and Or, 1996; Hodnett et al., 1990; Thompson et al., 2002). For example, Thompson et al. (2002) suggested to place tensiometers adjacent to the drip tape, midway between two plants within the row at a depth of 0.3 m, based on their previous observations of the volume where broccoli roots were at maximum density. Hodnett et al. (1990) recommended that tensiometers must be placed along the drip line, below the root zone, but inside the wetted zone. Coelho and Or (1996) suggested a physically based approach for sensor placement and demonstrated its validity for drip-irrigated corn. However, this approach requires information on spatial distribution of soil hydraulic properties and root growth and uptake patterns, which are typically not readily available. Due to the wide range in possible root distributions and soil variability, that affect water dynamics and sensor placement, a general approach to determine optimal tensiometer placement is not available. This study presents a new concept for determining the best location of tensiometer placement for managing high frequency drip irrigation systems.

The first problem is that root growth patterns are altered in response to changes in soil conditions such as: water availability, wetting patterns (Coelho and Or, 1996), matric head, soil impedance (Bar-Yosef and Lambert, 1981), nutrient availability (Hodge, 2004) and aeration (Shani et al., 1995). Although much work has been done to investigate the influence of various parameters on root growth patterns, little has been done to manipulate root growth in the field. In this paper, we propose a method to create a homogeneous volume around buried drippers using a synthetic material (geotextile). This material has high hydraulic conductivity and low mechanical impedance and therefore might be preferable for root growth. We hypothesize that this approach creates an optimal soil environment for irrigation scheduling and tensiometer. The second problem is the spatial variability of soil properties which affect water dynamics around buried drippers. Numerical simulation approaches, to illustrate and quantify the effect of heterogeneity on flow regimes, have been useful in many studies (Rubin and Or, 1993; Russo et al., 1998; Vereecken et al., 2007). This approach is utilized here to provide information about variability of ψ with high-frequency irrigation, under different heterogeneous soils to determine best locations for tensiometers.

The overall goal of this study was to develop a monitoring practice, for high frequency irrigation, that shows low CV in ψ, and has high sensitivity to water content changes (from uptake or irrigation). The specific objectives of this study were twofold: (1) to manipulate root growth to increase root density in a predetermined monitoring locations, and (2) to evaluate optimum tensiometer location using ψ measurements in heterogeneous soils.

2. Materials and methods

2.1. Geotextile drip interface (GDI)

This experiment was conducted in a research site in Rehovot, Israel. Two 16 mm diameter subsurface drip lines were installed in Rehovot sand (Table 1) at a depth of 15 cm, with integrated drippers (facing upward) every 50 cm and a discharge rate of 2.4 l h^{-1} (Netafim Ltd, Israel). The distance between the two drip lines was 100 cm. A group of five consecutive drippers in each line were wrapped with a layer of geotextile around them (GDI); a group of five buried drippers (BD) were left without a geotextile cover (Fig. 1A) and three drippers at each end of the drip line and between groups were considered margins. The geotextile sheet had a density of 0.5 kg m^{-2}, and the layer was 10 cm long and 2 mm thick. Corn (*Zea mays* L.) was grown along one line and Eggplant (*Solanum melongena* L.) along the second line from 6 May to 8 Jul 2011. Two plants were planted per dripper, one on either side of the line. These crops were chosen because of their different root system architectures, the corn having adventitious root system and the eggplant having a tap root system. Slow-release fertilizer (Osmocote, Scotts, Marysville, Ohio, USA) was evenly distributed along the lines at a quantity of 0.1 kg m^{-2}. The plants were irrigated twice a day for 2 h giving a total 9.6 mm day^{-1} which was 25% more than the highest potential transpiration to minimize water stress to the plants and allow salt leaching. After removal of the plants, 60-cm deep and 50-cm wide trenches were dug parallel to the lines so that the north walls of the trenches had the drip lines in them. The trenches were dug parallel to the laterals because the two treatments affect soil conditions in that dimension and not the perpendicular dimension. The roots were exposed with a fine spray of water on the walls and black-and-white photographs were taken using a digital camera (PowerShot S5 IS, Canon, Lake Success, New York, USA), each photograph with 3264 pixel horizontally and 2448 pixel vertically. Photographs were analyzed using MATLAB image analysis toolbox software (MathWorks, Natick, Massachusetts, USA). The photographs were transformed to binary matrices where pixels containing roots were given a value of 1 and pixels not containing roots were given a value of 0. The matrices were then divided into 1-cm layers, both horizontal and vertical (Fig. 1B), and root density was calculated as the sum of root pixels divided by the total sum of pixels in the layer.

Table 1
Hydraulic parameters for the van Genuchten (1980) model of soils in this study.

	θ_r	θ_s	α	n	K_s	l
	cm^3 cm^{-3}	cm^3 cm^{-3}	cm^{-1}	–	cm h^{-1}	–
Sandy loam	0.065	0.41	0.075	1.89	4.42	0.5
Loam	0.078	0.43	0.036	1.56	1.04	0.5
Rehovot sand	0.005	0.4	0.045	3.01	47.88	0.5
Geotextile	0.06	0.62	0.05	5.117	557	0.5

2.2. Numerical simulation

The HYDRUS 2D/3D code (Šimůnek et al., 2008) was used to simulate irrigation scenarios. The standard software package was extended to include a system-dependent boundary condition that triggers irrigation for a fixed duration when a specified ψ threshold is reached at a predetermined point in the flow domain (Dabach et al., 2013) resulting in a demand based irrigation system which depends directly on plant water uptake. In this work, the extended HYDRUS 2D/3D software was used to investigate the effect of tensiometer location in heterogeneous soils on the CV of tensiometer measurements, CV of total applied irrigation water, and drainage.

HYDRUS 2D/3D software numerically simulated two-dimensional water flow and root water uptake. The simulation domain consisted of a 0.75-m deep and 1-m wide sandy loam and loam soil profiles. A 1-cm diameter circle, representing the dripper, was located at the center of the flow domain, 25 cm below the upper boundary (Fig. 2B). The flow domain represents a field irrigated by strip sources with 1-m spacing between sources. The generated mesh grid had 2953 nodes, with a global mesh size of 3 cm and targeted mesh size of 1 cm around the dripper (Warrick and Lazarovitch, 2007). The flow domain consisted of either sandy loam or loam soils, both with a geotextile material surrounding the dripper. The parameters of the van Genuchten–Mualem hypothetic soils and geotextile hydraulic properties model (Mualem, 1976; van Genuchten, 1980) selected for numerical simulations are presented in Table 1. Hydraulic parameters of the geotextile